

## Effect of harvesting time on biomass and combustion quality of *Miscanthus lutarioriparius* in Dongting lake area

Peng ZHU<sup>1,3,4</sup>, Liang XIAO<sup>1,3,4</sup>, Sai YANG<sup>2,3,4\*</sup>

<sup>1</sup>Hunan Agricultural University, College of Bioscience and Biotechnology, Changsha 410128, China; [2468008190@qq.com](mailto:2468008190@qq.com); [xiaoliang@hunau.edu.cn](mailto:xiaoliang@hunau.edu.cn)

<sup>2</sup>Orient Science & Technology College of Hunan Agriculture University, Changsha 410128, China; [yangsai\\_1116@hunau.edu.cn](mailto:yangsai_1116@hunau.edu.cn) (\*corresponding author)

<sup>3</sup>Hunan Agricultural University, Hunan Engineering Laboratory for Ecological Application of *Miscanthus* Resources, Changsha, 410128, China

<sup>4</sup>Hunan Academy of Agricultural Science, Crop Research Institute, Changsha, 410128, China

### Abstract

Biomass energy, recognized for its potential to supplant traditional energy sources, finds a promising alternative in *Miscanthus*. Particularly, *M. lutarioriparius*, a species within the *Miscanthus* genus, stands out as the most suitable for application. This study focuses on the impact of harvest timing on the biomass and combustion quality of *M. lutarioriparius* in the coastal wetlands of Dongting Lake, Hunan. A comprehensive field experiment was conducted in this area. The findings reveal several key trends: Firstly, the biomass yield of *M. lutarioriparius* decreased from 18.42 tons per hectare to 11.25 tons per hectare with the delayed harvest. there is a notable increase in the stem-to-leaf ratio of *M. lutarioriparius*, primarily attributed to leaf shedding. Secondly, the water content had dropped to 22.33% by the time of harvest in February of the following year. Ash content decreased from 4.55% to 2.17% from October to February of the following year. The calorific value, cellulose and lignin content increased with delayed harvest, while hemicellulose content decreased. Notably, the calorific value exhibits a significant positive correlation with cellulose and lignin content, and a markedly negative correlation with hemicellulose. Thirdly, most mineral elements in the plant demonstrate a significant decrease with delayed harvesting, except for potassium (K) and calcium (Ca), which initially increase and then decrease. The ash content shows a positive correlation with the contents of potassium (K) and silicon (Si). Despite a reduction in biomass yield due to delayed harvesting, combustion quality significantly improves. Therefore, it is concluded that optimal fuel quality is achieved when *M. lutarioriparius* is harvested in February of the following year.

**Keywords:** biomass yield; harvesting time; *M. lutarioriparius*; quality

### Introduction

The escalating depletion of fossil fuels and the intensification of the global greenhouse effect have underscored the urgency in exploring renewable energy sources, a pursuit vital for energy security and

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sustainability (Höök *et al.*, 2013). This issue has ascended to a position of significant global concern. *Miscanthus lutarioriparius* is a member of the Poaceae family and endemic to China. It was considered an environmentally friendly and restorative species, making it a leading candidate among second-generation energy crops (Yi, 2012). The plant is primarily used for direct combustion and conversion into fuel ethanol. The yield and quality of biomass are crucial factors that affect its effective utilization. These aspects are substantially impacted by the timing of harvest (Bilandzija *et al.*, 2017; Dragoni *et al.*, 2017; Marin *et al.*, 2021). As energy plants develop, their biomass yield and quality vary (Kołodziej *et al.*, 2023; Rivera-Chacon *et al.*, 2023). This highlights the importance of harvesting biomass at the optimal time to maximise production efficiency.

*Miscanthus* biomass, which has a high mineral content, can pose challenges such as slagging, reactor blockage, and equipment corrosion during direct combustion processes (Surendra *et al.*, 2018). To address these issues, delaying the harvest has been implemented as a strategy. This approach aims to reduce water content, thereby lowering both harvesting and drying costs, as well as decreasing the ash content of the biomass. Consequently, this improves the quality and combustion efficiency of the biomass (Huisman *et al.*, 1997; Aurangzaib *et al.*, 2016). Additionally, delaying the harvest until spring leads to a significant reduction in the mineral nutrient content and biomass yield of *Miscanthus* dry matter (Lewandowski *et al.*, 2003). Simultaneously, such delay facilitates the translocation of nitrogen and other nutrients from the stems to the roots, enriching the nutrient reserve for *Miscanthus* growth in the subsequent growing season, and thus contributing to a reduction in production costs (Huisman *et al.*, 1997).

*M. lutarioriparius* predominantly thrives in the tidal flats of the Dongting Lake region, occupying approximately  $1.2 \times 10^5$  hectares of coastal area, with a potential yield of 1,100,000 tons annually in Hunan Province (Liao *et al.*, 2022). This species historically served as a primary raw material for paper production until 2017. Following the cessation of this industry, there has been a pressing need to explore new applications for *M. lutarioriparius*. Over the past decades, *Miscanthus* has been effectively utilized in the production of various industrial products, including a variety of chemicals, bio-ethanol (Lee *et al.*, 2015), biological materials (Girones *et al.*, 2016; Sun *et al.*, 2024), biofuel (Christian *et al.*, 2008) and vegetal concretes (Dias *et al.*, 2020). In the future, *M. lutarioriparius* shows potential as a suitable raw material for these and other industrial applications. The maintenance of biomass quality characteristics is critical to this transition. It is important to ensure consistency and suitability for diverse industrial uses.

This study conducted on comparative analyses of biomass yield and chemical composition at different harvest times of *M. lutarioriparius*. It also examined the relationship between combustion characteristics and the chemical composition of the biomass. The study aimed to evaluate the quality characteristics of biomass combustion over time and represents the first effort to outline temporal patterns in *M. lutarioriparius*'s biomass yield and chemical composition. The findings were used to determine the best time to harvest *M. lutarioriparius*, taking into account its various applications.

## Materials and Methods

### *Field trial and climatic conditions*

A field trial involving *M. lutarioriparius* was established in the 1990s at the experimental farm of Hunan Agriculture University, located in Yuan Jiang (28°59'5.94"N, 112°19'55.73"E), South Dongting Lake. The soil at the research site is classified as purple alluvial soil, with a pH of 7.22. The humus content in the soil was recorded at 12.93%. Additionally, the soil's macronutrient profile was analyzed, revealing nitrogen (N) content at 107.92 mg/kg, phosphorus (P) at 9.73 mg/kg, and potassium (K) at 340.15 mg/kg. Meteorological data,

including rainfall and temperature, were systematically collected and recorded by the meteorological station in Yuan Jiang City, as detailed in Table 1.

**Table 1.** Monthly precipitation and mean temperature during the study period

Month	Monthly precipitation(mm)	Monthly mean temperature (°C)
January	68	5.4
February	84.3	7.6
March	124.3	11.6
April	177.1	17.8
May	176.7	22.8
June	183.8	26.2
July	156.8	29.4
August	111	28.7
September	70.6	24.4
October	84.1	19.1
November	76.2	13.6
December	42.3	7.9

#### *Management of the trial*

In March 1994, a single genotype of *M. lutarioriparius* was planted to cover approximately 33 hectares with a planting density of 1 plant per square meter, achieved through a row spacing of 1×1 meter. No fertilizers have been administered since the inception of the trial. We ensured weed control through a combination of hand weeding and herbicide application, particularly during the first three years. We also conducted annual pest control using pesticides to maintain the health and integrity of the crop.

#### *Experimental design and sample collection*

The experiment was set up with six harvest period treatments, which were sampled about once a month on the 15th day of the month, starting from September 15, 2016, on 2017.09.15 (H1), 2017.10.15 (H2), 2017.11.15 (H3), 2017.12.15 (H4), 2018.01.15 (H5), 2018.02.15 (H6). During each harvesting session, *M. lutarioriparius* was collected from a 20 m<sup>2</sup> area (5×4 m) to ascertain the yield per unit area. This process was replicated three times for accuracy. To determine the leaf-stem ratio, stems and leaves were segregated at the leaf sheaths, and 20 plants per plot were weighed separately. Subsequently, 1 kg of biomass was randomly selected from each plot. The harvested biomass was dried in a circulating air oven at 60 °C for 48 hours to determine dry matter yield and moisture content. After drying, the samples were shredded and processed to a size that would pass a 1 mm sieve in preparation for subsequent mass analysis.

#### *Chemical analysis of the plant biomass*

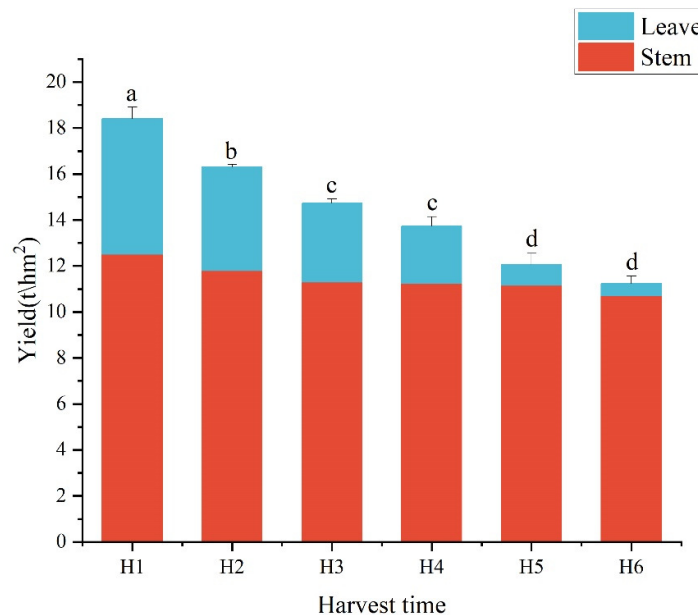
The ash content was determined by measuring the loss on ignition over a four-hour period at 550 °C. The calorific value of the samples was ascertained using a calorimeter (XRY-1a), which specifically measures the high calorific value. Cellulose, hemicellulose, and lignin contents were analyzed using the Van der Waals method. K and Na concentrations were determined via flame photometry. The P content was quantified using a vanadium molybdenum yellow spectrophotometer. The levels of Ca and Mg were determined using atomic absorption spectrophotometry after digestion in a solution of HNO<sub>3</sub>-HClO<sub>4</sub>. The evaluation of S content was carried out using the Eschka method. All the above experimental methods are referred to (Bao, 2000).

*Data processing and analysis*

Data were organized using Microsoft Excel 2019, measured data were subjected to one-way ANOVA (results expressed as mean  $\pm$  standard deviation) using SPSS Statistics 25.0 software, multiple comparisons were performed using Turkey's method, and a comprehensive evaluation was performed using Principal Component Analysis (PCA), and plotted in Origin 2021.

**Results***Effects of harvest time on the yield of harvestable biomass*

The variations in biomass yield and stem-leaf ratio of *M. lutarioriparius* harvested at different times was shown in Figure 1. A notable decline in biomass yield was observed as the harvest time was shifted, with significant differences between treatments ( $P < 0.05$ ). In September, *M. lutarioriparius* exhibited its highest yield, reaching 18.42 tons per hectare. Conversely, the lowest yield was recorded in February, at 11.25 tons per hectare, marking a 38.93% decrease from the September yield. Analysis of yield composition revealed that stem yield consistently surpassed leaf yield across all harvest periods, with no significant variations in stem yield between these periods. However, the leaf proportion in *M. lutarioriparius* biomass production progressively diminished with delayed harvesting. In September, the biomass production comprised 66.67% stem and 33.33% leaf. By February of the following year, this ratio shifted dramatically to 95.46% stem and 4.54% leaf. The total yield reduction of *M. lutarioriparius* was 7.17 tons per hectare, consisting of a 5.36 tons per hectare reduction in leaf yield and a 1.81 tons per hectare decrease in stem yield. Notably, the decrease in leaf yield accounted for 74.76% of the total reduction in biomass yield. Therefore, it can be inferred that the primary cause of yield reduction in delayed harvests of *M. lutarioriparius* is attributable to the significant decrease in leaf yield.

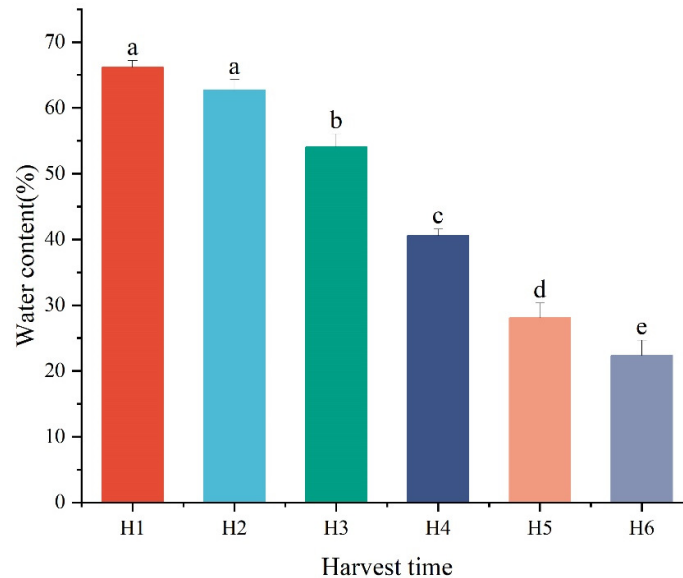


**Figure 1.** Effect of harvest time on biomass yield of *M. lutarioriparius*

Note: Different lowercase letters in the figure indicate that the different treatments are significantly different at the 0.05 level ( $P < 0.05$ )

*Effect of harvesting time on the moisture content of biomass*

The water content in *M. lutarioriparius* exhibited a gradual decrease with the postponement of harvest time, as illustrated in Figure 2. From September to October, the water content remained above 60%, with no significant difference observed between these two periods. However, a notable decrease to 54.03% was recorded in mid-November, which was significantly different from the water content levels observed during the September and October harvests ( $P < 0.05$ ). Subsequently, *M. lutarioriparius* entered a phase of rapid decline in water content. By the time of the February harvest in the following year, the water content had fallen to 22.33%, only 33.75% of the level recorded in September. This trend highlights the pronounced effect of delayed harvesting on the water content of *M. lutarioriparius*.

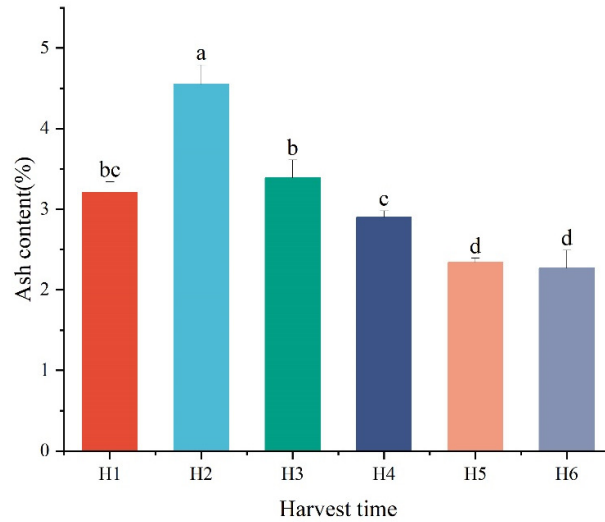


**Figure 2.** Effect of harvest time on water content of *M. lutarioriparius*.

Note: Different lowercase letters in the figure indicate that the different treatments are significantly different at the 0.05 level ( $P < 0.05$ )

*Effect of harvesting time on ash mass fraction of M. lutarioriparius biomass*

Figure 3 depicts the variation in ash content of *M. lutarioriparius*, which initially increased and then decreased as the harvest time was delayed. The peak ash content of 4.55% was observed in October. After this peak, a gradual reduction in ash content was noted. Specifically, the ash content of samples harvested in January and February of the following year was recorded at 2.34% and 2.17%, respectively, with no significant difference discernible between these two periods. In particular, when *M. lutarioriparius* was harvested in January of the following year, the ash content exhibited a reduction of 48.45% compared to the October harvest. This trend underscores the impact of harvest timing on the ash content of *M. lutarioriparius* biomass.

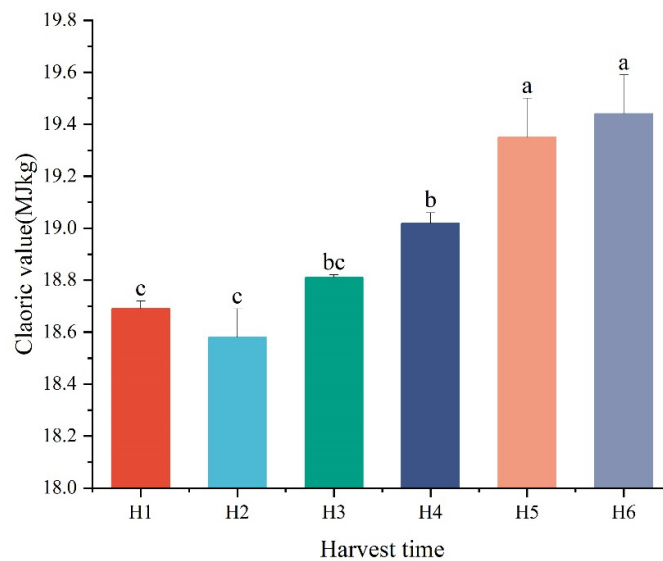


**Figure 3.** Effect of harvest time on ash content of *M. lotarioriparius*

Note: Different lowercase letters in the figure indicate that the different treatments are significantly different at the 0.05 level ( $P < 0.05$ )

*Effect of harvesting time on the calorific value of M. lotarioriparius biomass*

The calorific value of *M. lotarioriparius* showed a fluctuating trend with the delay of harvest time, as evidenced in Figure 4. Initially, the calorific value decreased, followed by an increase, but no significant difference was observed between the months of September and October. However, a significant variation in calorific value was observed in samples harvested in October, November, December, and January of the following year. Contrarily, the calorific values of *M. lotarioriparius* harvested in January and February of the following year did not show a significant difference. Specifically, the calorific value for the October harvest was recorded at 18.58 MJ/kg, whereas the calorific value for the February harvest reached 19.58 MJ/kg. This pattern highlights the nuanced influence of harvest timing on the energy content of *M. lotarioriparius* biomass.

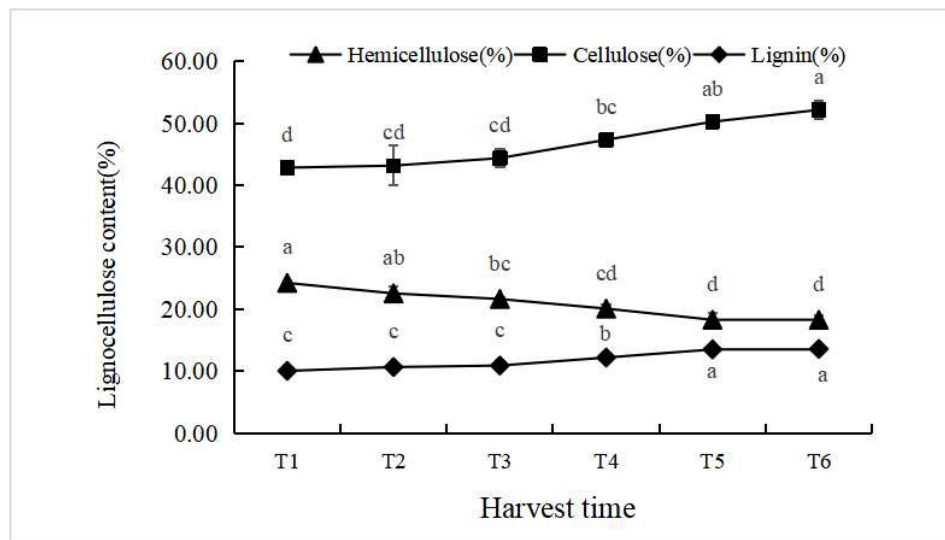


**Figure 4.** Effect of harvest time on calorie value of *M. lotarioriparius*

Note: Different lowercase letters in the figure indicate that the different treatments are significantly different at the 0.05 level ( $P < 0.05$ )

*Effect of harvesting time on the lignocellulose content of M. lutarioriparius*

The main components of *M. lutarioriparius* biomass include cellulose, hemicellulose, and lignin, which are also the main substances used in biomass for energy production, with their respective contents determining the biomass energy potential. Figure 5 illustrates the variations in lignocellulose content of *M. lutarioriparius* at different harvest times. A gradual increase in the content of cellulose and lignin in *M. lutarioriparius* biomass was observed with delayed harvest time, whereas the content of hemicellulose exhibited a corresponding decrease. Specifically, the cellulose content of *M. lutarioriparius* harvested in September was 42.84%. The cellulose content did not show significant differences between the first three months and the last two months of the study period ( $P > 0.05$ ). By the time of the February harvest, the cellulose content increased to 52.16%. The variation in hemicellulose content displayed significant differences in October, December, and January of the following year ( $P < 0.05$ ). In September, the hemicellulose content was 24.23%, which decreased by 5.96% in the February harvest of the following year. Regarding lignin content, it was 10.03% in September and increased to 13.58% by the February harvest, with notable differences observed in the December and January data. This trend underlined the influence of the time of harvest on the lignocellulosic composition of *M. lutarioriparius* biomass.



**Figure 5.** Effect of harvest time on lignocellulose content of *M. lutarioriparius*

Note: Different lowercase letters on each curve in the graph indicate that the treatments are significantly different at the 0.05 level ( $P < 0.05$ ).

*Effect of harvesting time on the mineral element content of M. lutarioriparius biomass*

The content of mineral elements in biomass is a crucial indicator of biomass quality. In particular, the Si/K ratio is significantly correlated with the degree of slagging during biomass combustion. As delineated in Table 2, the mass fractions of S, Na, Mg, K, P, Ca, and Si in *M. lutarioriparius* biomass showed a general downward trend with delayed harvest time. However, the mass fractions of K and Si initially increased and then decreased. Compared to the September harvest, the S content showed the most significant decrease with 55.74%, followed by decreases of 53.8% and 52.02% for Ca and P, respectively, and decreases of 48.40% and 46.41% for Na and Mg, respectively. The lowest mass fractions of K and Si, observed in the H6 period, were 44.53% and 53.84% lower, respectively, than their highest values in the H2 period. These trends highlight the significant impact of harvest timing on the mineral composition of *M. lutarioriparius* biomass, with implications for its combustion characteristics.

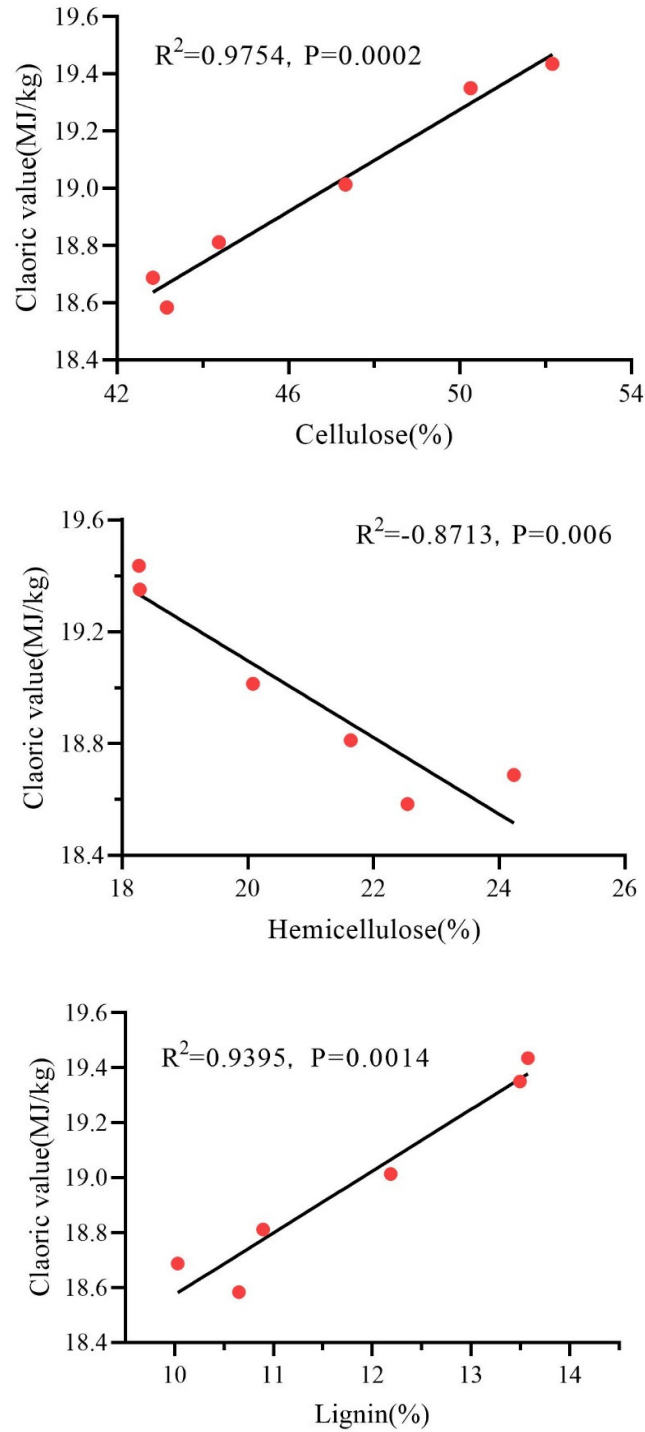
**Table 2.** Effect of harvest time on mineral element contents in *M. lutarioriparius* biomass (Mean  $\pm$  SD)

Harvest time	S (mg/kg)	Na (mg/kg)	K (mg/kg)	P (mg/kg)	Mg (mg/kg)	Ca (mg/kg)	Si (g/kg)
H1	1985.67 $\pm$ 146.20a	73.60 $\pm$ 3.28a	7015.15 $\pm$ 14.65b	2330.25 $\pm$ 13.66a	266.30 $\pm$ 5.15a	864.20 $\pm$ 14.64a	7.90 $\pm$ 0.04b
H2	1972.00 $\pm$ 102.01a	53.99 $\pm$ 2.43b	9675.20 $\pm$ 65.25a	1846.70 $\pm$ 22.26b	214.75 $\pm$ 4.25b	752.25 $\pm$ 17.35b	11.70 $\pm$ 0.02a
H3	1719.33 $\pm$ 52.35b	49.39 $\pm$ 2.35bc	6735.50 $\pm$ 32.05c	1668.45 $\pm$ 4.45c	201.90 $\pm$ 4.65c	526.65 $\pm$ 12.75c	6.30 $\pm$ 0.02c
H4	1211.00 $\pm$ 30.81c	49.14 $\pm$ 0.28bc	5649.70 $\pm$ 53.75d	1538.55 $\pm$ 12.25d	157.90 $\pm$ 1.75d	484.50 $\pm$ 21.74d	5.80 $\pm$ 0.02d
H5	1021.33 $\pm$ 33.72cd	43.62 $\pm$ 2.94cd	5368.60 $\pm$ 23.95e	1304.75 $\pm$ 2 3.56e	146.50 $\pm$ 3.45e	466.70 $\pm$ 15.26d	5.41 $\pm$ 0.05e
H6	879.33 $\pm$ 75.96d	38.00 $\pm$ 1.82d	5366.50 $\pm$ 15.45e	1188.20 $\pm$ 11.36f	142.70 $\pm$ 1.35e	414.60 $\pm$ 4.55e	5.30 $\pm$ 0.02f

Note: Different letters in the same column indicate significant differences ( $P < 0.05$ ).

#### *Correlation analysis between the lignocellulose content and calorific value of M. lutarioriparius*

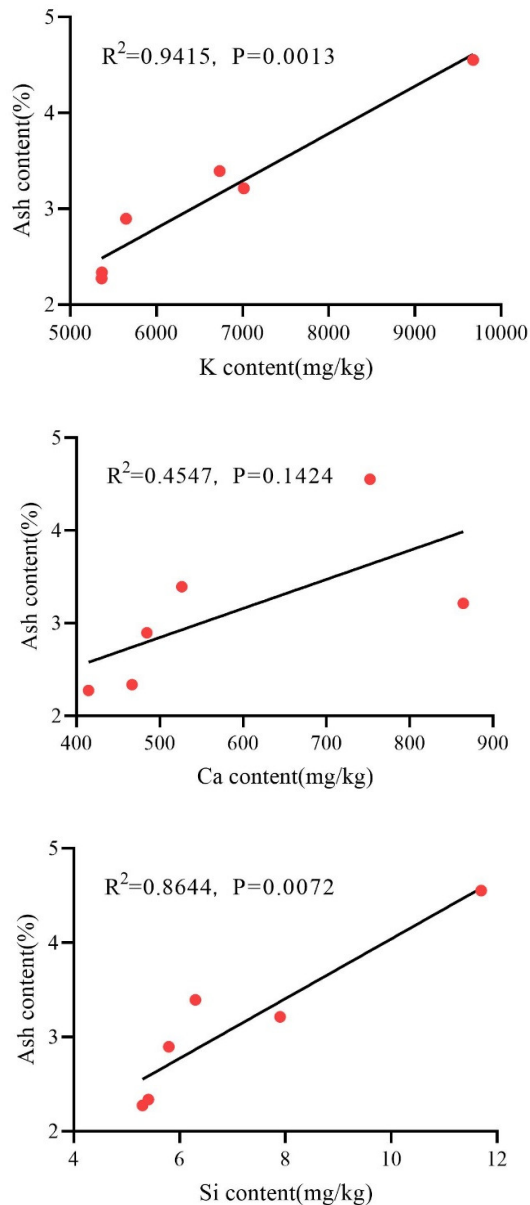
The lignocellulose content of *M. lutarioriparius* was crucial for nutrient harvesting. The variation in the levels of these substances had a significant impact on their further utilization, whether as a material for direct combustion or in biological fermentation processes. An analysis of the relationship between lignocellulose content and calorific value, as shown in Figure 6, reveals a positive correlation between the calorific value and the contents of cellulose and lignin, achieving a highly significant level ( $P < 0.01$ ). Conversely, hemicellulose exhibited a negative correlation with calorific value, also reaching a significant level ( $P < 0.01$ ). Consequently, in the production of *M. lutarioriparius* biomass, it becomes imperative to focus on enhancing the content of cellulose and lignin within the biomass to increase its energy output. This approach was essential to optimise the biomass for energy production and maximizing its utility in various applications.



**Figure 6.** Correlation analysis between lignocellulose content and calorific value  
\*\*: $P<0.01$ ; \*: $P<0.05$

*Correlation analysis between the content of major mineral elements and ash*

The ash content in the biomass is closely related to the concentrations of K, Ca, and Si in the biomass. Figure 7 illustrated that the ash content in *M. lutarioriparius* biomass exhibits a positive correlation with the levels of the elements K, Ca, and Si elements. In particular, the correlation between the content of K and Si and the ash content is highly significant, as indicated by the statistical value ( $P < 0.01$ ). This finding underscores the importance of these mineral elements in determining the ash content of *M. lutarioriparius* biomass, a factor that is crucial in assessing its suitability for various applications, particularly in energy production and combustion processes.



**Figure 7.** Correlation analysis between element content and ash  
 \*\*:  $P < 0.01$ ; \*:  $P < 0.05$

*Synthesized assessment*

The agricultural data pertaining to yield and quality, collected across various harvest time, underwent a process of standardization to ensure uniformity. Subsequently, these standardized datasets were analyzed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity to ascertain their suitability for principal component analysis (PCA). The KMO value of 0.810 exceeded the threshold of 0.6, and the datasets successfully met the criteria for sphericity as per Bartlett's test ( $P < 0.05$ ), thereby confirming their adequacy for PCA.

The data were rotated using the Varimax method, which yielded two principal components (PCs) with eigenvalues greater than one, specifically 5.861 and 1.033. Table 3 reveals that the first principal component (PC1), accounting for 73.267% of the variance, encapsulates the chemical composition and structural factors of *M. lutarioriparius*, including hemicellulose, leaf-to-stem ratio, water content, cellulose, lignin, and yield. The second principal component (PC2), addressing the plant's combustion characteristics and energy yield factors, primarily involves calorific value and ash content. With a combined contribution rate of 86.175%, PCs 1 and 2 effectively capture the essence of the data, surpassing the 80% threshold for a robust representation.

**Table 3.** Post-rotation factor loading coefficient matrix, eigenvalues, and contribution of yield and quality indicators at different harvest times

Indicator or parameter	Principal component	
	PC1	PC2
Hemicellulose content	0.908	0.279
Leaf-stem ratio	0.68	0.584
Water content	0.813	0.551
Cellulose content	0.915	0.134
Lignin content	0.709	0.29
Yield	-0.938	-0.216
Ash content	0.592	0.736
Calorie value	-0.096	-0.976
Eigenvalue	5.861	1.033
Contribution rate (%)	73.267	12.908
Cumulative contribution rate (%)	73.267	86.175

Through principal component analysis, PC1 and PC2 were selected to represent the quality and yield characteristics of *M. lutarioriparius* across different harvest time, replacing the original eight indicators. The functional expressions for PC1 and PC2, derived from the characteristic vectors of the different indicators, are as follows:

$$Y1 = 0.255 \cdot \text{Hemicellulose} - 0.031 \cdot \text{Ash} + 0.058 \cdot \text{Leaf-stem ratio} + 0.121 \cdot \text{Moisture Content} + 0.310 \cdot \text{Cellulose} + 0.174 \cdot \text{Lignin} + 0.311 \cdot \text{Calorific Value} - 0.290 \cdot \text{Yield}$$

$$Y2 = -0.115 \cdot \text{Hemicellulose} + 0.340 \cdot \text{Ash} + 0.194 \cdot \text{Leaf to Stem ratio} + 0.122 \cdot \text{Moisture Content} - 0.226 \cdot \text{Cellulose} - 0.036 \cdot \text{Lignin} - 0.696 \cdot \text{Calorific Value} + 0.174 \cdot \text{Yield}$$

$$\text{Comprehensive evaluation score} = 0.657 \cdot Y1 + 0.343 \cdot Y2$$

By substituting the data from different harvest time into these equations, a comprehensive evaluation index for *M. lutarioriparius* during each period can be obtained (Table 4). The integrated ranking of *M. lutarioriparius* from highest to lowest is H6 > H5 > H4 > H3 > H2 > H1, indicating that *M. lutarioriparius* harvested during period H6 yields the best quality and quantity.

**Table 4** Composite evaluation index of *M. lutarioriparius* in different sampling periods

Harvest time	Principal component score (Y1)	Principal component score (Y2)	Comprehensive evaluation score	Ranking
H1	-1.827	1.007	-0.854	6
H2	-0.432	-1.219	-0.702	5
H3	-0.033	-1.045	-0.380	4
H4	0.455	-0.383	0.167	3
H5	0.804	0.407	0.668	2
H6	1.033	1.233	1.102	1

## Discussion

### *Relationship between harvesting time and biomass yield*

Biomass yield serves as a critical metric for assessing the viability of plants as sources of biomass energy or feedstock (Aurangzaib *et al.*, 2016). Plant biomass typically followed a life cycle characterized by an initial increase followed by a decline. *M. lutarioriparius*, a perennial rhizome herb, exemplifies this cycle. Its underground rhizomes germinate annually, giving rise to new plants that eventually reach a peak in biomass. Concurrently, these new plants produce underground stems, transferring nutrients and mineral elements from above-ground parts to the underground rhizomes (Guretzky *et al.*, 2011; Serapiglia *et al.*, 2016). This process not only fosters the growth of the rhizomes but also accumulates reserves for the subsequent season's germination and growth (Sanderson *et al.*, 1999). Therefore, determining the optimal harvest time is crucial for maximizing biomass yield and ensuring nutrient accumulation in underground stems, thereby facilitating the generational renewal of *M. lutarioriparius*.

The results of this study indicated a significant effect of harvesting time on *M. lutarioriparius* yield, with a gradual decrease as harvesting is delayed. In Europe, delaying the harvest of Miscanthus to winter resulted in a 14-15% decrease in biomass production (Lewandowski *et al.*, 2003). In the United States, the cultivation of switchgrass as an energy plant and its delayed harvest similarly yield high-quality biomass but at a reduced quantity (Ogden *et al.*, 2010). In China, using corn straw as biomass fuel with a delayed spring harvest leads to a 47.7% delayed in biological yield (Liu *et al.*, 2009). The primary factors contributing to this decrease in biomass production included plant respiration, biodegradation, leaching from rain and snow, and mechanical loss (Hadders *et al.*, 1997). In the context of this experiment, the leaves of *M. lutarioriparius*, located in a lake area with a strong winter monsoon and frequent rainfall, become yellow and prone to falling post-maturity. This leads to a significant loss of leaves, upper stems, and ears, thereby substantially reducing the biomass yield.

### *Relationship between harvesting time and biomass fuel quality*

While delayed harvest negatively impacts biomass production, it positively influences biomass quality, as highlighted by Wilson, *et al.* (Wilson *et al.*, 2013). Firstly, delayed harvesting resulted in a reduction in the water content of *M. lutarioriparius*, which helped to reduce the costs associated with harvest, transportation, and storage (Sosa *et al.*, 2015), while enhancing utilization efficiency (Lewandowski *et al.*, 2003). Secondly, the reduction in mineral elements in *M. lutarioriparius* biomass lowers the ash content (Adler *et al.*, 2006). Notably, the diminished K/Si ratio decreases the slagging during biomass combustion (Baxter *et al.*, 1998), and the return of mineral elements to the soil minimizes nutrient loss (Parrish *et al.*, 2021). Thirdly, delayed harvest caused a gradual decrease in plant cell content and an increase in cell wall fiber, thereby elevating the lignocellulose content in plants (Adler *et al.*, 2006). Fourthly, such delay enhances the cellulose and lignin content in the biomass, consequently increasing its calorific value (Hodgson *et al.*, 2010). In this study, *M.*

*lutarioriparius* exhibited the lowest calorific value in October, possibly due to the high content of non-structural carbohydrates present at this stage. This comprehensive assessment underscores the multiple effects of harvest timing on the quality and efficiency of *M. lutarioriparius* as a biomass resource.

#### *Relationship between harvesting time and mineral element content*

Delayed harvesting significantly reduced the content of mineral elements in biomass, thereby enhancing biomass quality, as evidenced by studies such as Ameen and Kusvuran (Ameen *et al.*, 2019; Kusvuran *et al.*, 2022). Research indicates that delayed harvesting significantly affects the nitrogen, potassium, chlorine, and phosphorus content in *Miscanthus sinensis* and *Miscanthus sacchariflorus*, major herbaceous energy plants. For instance, Huisman (Huisman *et al.*, 1997) observed that the nitrogen content in autumn-harvested biomass was significantly higher than in winter. Lewandowski (Lewandowski *et al.*, 2003) found a significant reduction in potassium content when harvesting was delayed until the following spring. Such delay results in a gradual decrease in mineral elements in biomass, due in part to the dissolution by precipitation, affecting elements like Cl, K, N, and S (Adler *et al.*, 2006). This reduction diminishes the emission of harmful gases such as NO<sub>x</sub> and SO<sub>2</sub> (Iqbal *et al.*, 2015; Rancāne *et al.*, 2016) and curtails fertilizer usage, thereby reducing input costs (Casler, 2023).

In this study, the mineral elements in *M. lutarioriparius* biomass also decreased due to delayed harvest. Primarily, delayed harvest shifted the growth centre of *M. lutarioriparius* from the aboveground to the belowground part, resulting in the downward transport of mobile mineral elements and decreasing their concentration in the aboveground biomass (Cosentino *et al.*, 2014). Additionally, this phenomenon may be associated with winter rainfall in Hunan, where rainwater leaching reduced the mineral content of biomass (Kusvuran *et al.*, 2022). There was also a transfer of mineral elements to the belowground part prior to plant decline (Strullu *et al.* 2011). Moreover, the proportion of leaves in biomass production decreases (Kludze *et al.*, 2013; Iqbal *et al.*, 2015). By February of the following year, leaves constitute only 4.54% of *M. lutarioriparius* biomass production, and as the mineral content in leaves is higher than in stems, leaf litter significantly contributes to the overall decrease in mineral elements. This comprehensive analysis underscores the multifaceted impact of delayed harvest on the mineral composition of *M. lutarioriparius*.

#### *Determination of optimal harvest time*

Currently, numerous studies have indicated that while delayed harvesting may lead to a reduction in the biomass yield of energy crops, it can simultaneously enhance the quality of the biomass as a fuel. For instance, Lewandowski *et al.* (2003) observed in their field trials in southern Germany that a later harvest of *Miscanthus × giganteus* resulted in decreased biomass production. However, this postponement improved the combustion quality and reduced ash and pollutant emissions (Lewandowski *et al.*, 2003). Parrish and associates conducted similar field experiments in the United States on the productivity and quality of *Miscanthus × giganteus* at different harvest times, demonstrating that delayed harvesting not only enhances the combustion characteristics but also optimizes the long-term productivity of the energy crop (Parrish *et al.*, 2021). These findings align with the results of the present study. A comprehensive assessment suggests that harvesting *M. lutarioriparius* in mid-February of the following year could enhance its sustainability and economic benefits as a bioenergy crop.

## **Conclusions**

As the harvest time of *M. lutarioriparius* was delayed, an increase in leaf litter occurs, consequently diminishing the overall yield of the plant. However, this delayed harvesting strategy also led to a reduction

in the water, ash, and mineral element content in the biomass of *M. lutarioriparius*, while simultaneously enhancing the cellulose and lignin content. These changes significantly improved the quality of the biomass. The mechanisms contributing to the decreased mineral element content in Hunan likely involve the transference of mineral nutrients, leaching by rain and snow, and leaf shedding. During the winter months, the moisture and ash contents of *M. lutarioriparius* are significantly lower than those observed during the ripening period, indicating stability. At the same time, there is a significant reduction in mineral content, which contributes to improved fuel quality. Therefore, the fuel quality of *M. lutarioriparius* harvested at the February proves to be more advantageous for combustion power generation purposes, in line with the observed improvements in biomass composition and quality during this period.

### Authors' Contributions

Conceptualization, P.Z. and S.Y.; methodology, L.X.; software, P.Z.; validation, P.Z. and L.X.; formal analysis, L.X. and S.Y.; investigation, P.Z.; resources, P.Z. and L.X.; data curation, P.Z. and S.Y.; writing—original draft preparation, P.Z. and L.X.; writing—review and editing, S.Y.; visualization, S.Y.; supervision, S.Y.; project administration, S.Y. All authors read and approved the final manuscript.

### Ethical approval (for researches involving animals or humans)

Not applicable.

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### Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

### References

- Adler PR, Sanderson MA, Boateng AA, Weimer PJ, Jung H-G (2006). Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agronomy Journal* 98(6):1518-1525. <https://doi.org/10.2134/agronj2005.0351>
- Ameen A, Liu J, Han L, Xie GH (2019). Effects of nitrogen rate and harvest time on biomass yield and nutrient cycling of switchgrass and soil nitrogen balance in a semiarid sandy wasteland. *Industrial Crops and Products* 136:1-10. <https://doi.org/10.1016/j.indcrop.2019.04.066>
- Aurangzaib M, Moore KJ, Archontoulis SV, Heaton EA, Lenssen AW, Fei S (2016). Compositional differences among upland and lowland switchgrass ecotypes grown as a bioenergy feedstock crop. *Biomass and Bioenergy* 87:169-177. <https://doi.org/10.1016/j.biombioe.2016.02.017>
- Bao SD (2000). *Soil and Agricultural Chemistry Analysis*. China Agriculture Press China Agriculture Press, Beijing, pp 178-200.

- Baxter LL, Miles TR, Miles TR, Jenkins BM, Milne T, Dayton D, Bryers RW, Oden LL (1998). The behavior of inorganic material in biomass-fired power boilers: field and laboratory experiences. *Fuel Processing Technology* 54(1):47-78. [https://doi.org/10.1016/S0378-3820\(97\)00060-X](https://doi.org/10.1016/S0378-3820(97)00060-X)
- Bilandzija N, Jurisic V, Voca N, Leto J, Matin A, Sito S, Kricka T (2017). Combustion properties of *Miscanthus x giganteus* biomass – Optimization of harvest time. *Journal of the Energy Institute* 90(4):528-533. <https://doi.org/10.1016/j.joei.2016.05.009>
- Casler MD (2023). Nitrogen fertilization and harvest management of switchgrass: impacts on biomass yield and nitrogen removal. *BioEnergy Research* 16(1):369-378. <https://doi.org/10.1007/s12155-022-10435-z>
- Christian DG, Riche AB, Yates NE (2008). Growth, yield and mineral content of *Miscanthus x giganteus* grown as a biofuel for 14 successive harvests. *Industrial Crops and Products* 28(3):320-327. <https://doi.org/10.1016/j.indcrop.2008.02.009>
- Cosentino SL, Scordia D, Sanzone E, Testa G, Copani V (2014). Response of giant reed (*Arundo donax* L.) to nitrogen fertilization and soil water availability in semi-arid Mediterranean environment. *European Journal of Agronomy* 60:22-32. <https://doi.org/10.1016/j.eja.2014.07.003>
- Dias PP, Waldmann D (2020). Optimisation of the mechanical properties of *Miscanthus* lightweight concrete. *Construction and Building Materials* 258:119643. <https://doi.org/10.1016/j.conbuildmat.2020.119643>
- Dragoni F, Giannini V, Ragaglini G, Bonari E, Silvestri N (2017). Effect of harvest time and frequency on biomass quality and biomethane potential of common reed (*Phragmites australis*) under paludiculture conditions. *BioEnergy Research* 10(4):1066-1078. <https://doi.org/10.1007/s12155-017-9866-z>
- Girones J, Vo L, Arnoult S, Brancourt-Hulmel M, Navard P (2016). *Miscanthus* stem fragment – Reinforced polypropylene composites: Development of an optimized preparation procedure at small scale and its validation for differentiating genotypes. *Polymer Testing* 55:166-172. <https://doi.org/10.1016/j.polymertesting.2016.08.023>
- Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J (2011). Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant and Soil* 339(1):69-81. <https://doi.org/10.1007/s11104-010-0376-4>
- Hadders G, Olsson R (1997). Harvest of grass for combustion in late summer and in spring. *Biomass and Bioenergy* 12(3):171-175. [https://doi.org/10.1016/S0961-9534\(96\)00047-5](https://doi.org/10.1016/S0961-9534(96)00047-5)
- Hodgson EM, Lister SJ, Bridgwater AV, Clifton-Brown J, Donnison IS (2010). Genotypic and environmentally derived variation in the cell wall composition of *Miscanthus* in relation to its use as a biomass feedstock. *Biomass and Bioenergy* 34(5):652-660. <https://doi.org/10.1016/j.biombioe.2010.01.008>
- Höök M, Tang X (2013). Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy* 52:797-809. <https://doi.org/10.1016/j.enpol.2012.10.046>
- Huisman W, Venturi P, Molenaar J (1997). Costs of supply chains of *Miscanthus giganteus*. *Industrial Crops and Products* 6(3):353-366. [https://doi.org/10.1016/S0926-6690\(97\)00026-5](https://doi.org/10.1016/S0926-6690(97)00026-5)
- Iqbal Y, Gauder M, Claupein W, Graeff-Hönninger S, Lewandowski I (2015). Yield and quality development comparison between miscanthus and switchgrass over a period of 10 years. *Energy* 89:268-276. <https://doi.org/10.1016/j.energy.2015.05.134>
- Kludze H, Deen B, Dutta A (2013). Impact of agronomic treatments on fuel characteristics of herbaceous biomass for combustion. *Fuel Processing Technology* 109:96-102. <https://doi.org/10.1016/j.fuproc.2012.09.043>
- Kusvuran A, Nazli RI, Tansi V, Ozturk HH, Budak DB (2022). Evaluation of harvest time effects on the combustion quality of warm- and cool-season perennial grasses in two contrasting semi-arid environments. *Industrial Crops and Products* 186:115260. <https://doi.org/10.1016/j.indcrop.2022.115260>
- Lee W-C, Kuan W-K (2015). *Miscanthus* as cellulosic biomass for bioethanol production. *Biotechnology Journal* 10(6):840-854. <https://doi.org/10.1002/biot.201400704>
- Lewandowski I, Heinz A (2003). Delayed harvest of miscanthus—influences on biomass quantity and quality and environmental impacts of energy production. *European Journal of Agronomy* 19(1):45-63. [https://doi.org/10.1016/S1161-0301\(02\)00018-7](https://doi.org/10.1016/S1161-0301(02)00018-7)
- Lewandowski I, Clifton-Brown JC, Andersson B, Basch G, Christian DG, Jørgensen U, Jones MB, Riche AB, Schwarz KU, Tayebi K, Teixeira F (2003). Environment and harvest time affects the combustion qualities of *Miscanthus* genotypes. *Agronomy Journal* 95(5):1274-1280. <https://doi.org/10.2134/agronj2003.1274>

- Liao XH, Wu YN, Fu TC, Iqbal Y, Yang S, Li M, Yi ZL, Xue S (2022). Biomass quality variations over different harvesting regimes and dynamics of heavy metal change in *Miscanthus lutarioriparius* around Dongting Lake. *Agronomy-Basel* 12(5):12. <https://doi.org/10.3390/agronomy12051188>
- Liu JL, Cheng X, Xie GH, Zhu WB, Xiong SJ (2009). Variation in corn stover yield and fuel quality with harvest time. 2009 Asia-Pacific Power and Energy Engineering Conference.
- Marin FR, Rattalino Edreira JL, Andrade JF, Grassini P (2021). Sugarcane yield and yield components as affected by harvest time. *Sugar Tech* 23(4):819-826. <https://doi.org/10.1007/s12355-020-00945-5>
- Ogden CA, Ileleji KE, Johnson KD, Wang Q (2010). In-field direct combustion fuel property changes of switchgrass harvested from summer to fall. *Fuel Processing Technology* 91(3):266-271. <https://doi.org/10.1016/j.fuproc.2009.10.007>
- Parrish AS, Lee M-S, Voigt TB, Lee DK (2021). *Miscanthus* × *giganteus* responses to nitrogen fertilization and harvest timing in Illinois, USA. *BioEnergy Research* 14(4):1126-1135. <https://doi.org/10.1007/s12155-021-10244-w>
- Rancāne S, Karklins A, Lazdina D, Berzins P, Bardule A, Butlers A, Lazdiņš A (2016). The evaluation of biomass yield and quality of *Phalaris arundinacea* and *Festulolium* fertilised with bio-energy waste products. *Agronomy Research* 14(1):198-210.
- Sanderson MA, Read JC, Reed RL (1999). Harvest management of switchgrass for biomass feedstock and forage production. *Agronomy Journal* 91(1):5-10. <https://doi.org/10.2134/agronj1999.00021962009100010002x>
- Serapiglia MJ, Boateng AA, Lee DK, Casler MD (2016). Switchgrass harvest time management can impact biomass yield and nutrient content. *Crop Science* 56(4):1970-1980. <https://doi.org/10.2135/cropsci2015.08.0527>
- Sosa A, Acuna M, McDonnell K, Devlin G (2015). Managing the moisture content of wood biomass for the optimisation of Ireland's transport supply strategy to bioenergy markets and competing industries. *Energy* 86:354-368. <https://doi.org/10.1016/j.energy.2015.04.032>
- Strullu L, Cadoux S, Preudhomme M, Jeuffroy MH, Beaudoin N (2011). Biomass production and nitrogen accumulation and remobilisation by *Miscanthus* × *giganteus* as influenced by nitrogen stocks in belowground organs. *Field Crops Research* 121(3):381-391. <https://doi.org/10.1016/j.fcr.2011.01.005>
- Sun P, Cheng L, Chen S, Xie M, Dong F, Dong X (2024). Nickel foam based monolithic catalyst supporting transition metal oxides for toluene combustion: Experimental and theoretical study of interfacial synergistic oxidation and water resistance. *Chemical Engineering Journal* 483:149176. <https://doi.org/10.1016/j.cej.2024.149176>
- Surendra KC, Ogoshi R, Zaleski HM, Hashimoto AG, Khanal SK (2018). High yielding tropical energy crops for bioenergy production: Effects of plant components, harvest years and locations on biomass composition. *Bioresource Technology* 251:218-229. <https://doi.org/10.1016/j.biortech.2017.12.044>
- Wilson DM, Dalluge DL, Rover M, Heaton EA, Brown RC (2013). Crop management impacts biofuel quality: influence of switchgrass harvest time on yield, nitrogen and ash of fast pyrolysis products. *BioEnergy Research* 6(1):103-113. <https://doi.org/10.1007/s12155-012-9240-0>
- Yi ZL (2012). Exploitation and utilization of *Miscanthus* as energy plant. *Journal of Hunan Agricultural University (Natural Sciences)* 38(05):455-463. <https://doi.org/10.3724/SP.J.1238.2012.00455>



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